Possible use of quadrant antennas for clandestine shortwave broadcasting: A technical assessment of Cold War number station operations from Bulgaria

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A retrospective RF propagation and antenna systems analysis

Subject:	Antenna suitability for clandestine HF broadcasting
Period:	Cold War era, approximately 1950–1989
Region:	Bulgaria (transmitter) to Central and Eastern Europe, Mediterranean, and Near East (reception)

This document presents a technical feasibility assessment only. All propagation calculations are based on publicly available antenna engineering data and standard ITU-R skywave propagation methodology. No classified sources have been consulted or referenced.

Abstract

This paper examines the technical suitability of horizontally polarised quadrant antennas—specifically the Wells cage quadrant and the single-wire cut-delta variant described by Beaumont—for clandestine shortwave broadcasting associated with Cold War number station operations originating from the Sofia region of Bulgaria. Three candidate transmitter sites in the vicinity of Sofia are assessed: Pobit Kamak (near Vakarel), Gorna Malina, and Momina Skala on Vitosha Mountain. Link budget calculations demonstrate that these sites, equipped with quadrant antennas operating between 7 MHz and 15 MHz, could achieve reliable ionospheric skywave coverage across an arc spanning Austria, Germany, Italy, Switzerland, Turkey, Greece, Cyprus, and Israel using transmitter powers as low as 10 W to 500 W, well within the operational capability of covert or semi-covert broadcast infrastructure. The omnidirectional azimuth pattern of the quadrant antenna is identified as the principal feature rendering it uniquely advantageous for simultaneously addressing agents dispersed across a broad geographic arc from a single fixed transmitter and frequency.

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1 Introduction

1.1 Number stations: a brief contextual summary

Number stations are clandestine shortwave broadcasting services, typically operated by state intelligence agencies, which transmit sequences of spoken digits, phonetic letters, or Morse code groups. These transmissions serve as a one-way communications channel to field agents or foreign assets, who decode the message using a pre-arranged one-time pad (OTP). The inherent asymmetry of the channel—the receiver need never transmit and therefore cannot be triangulated—made this method operationally attractive throughout the Cold War era and beyond.

Although the precise origins and operators of most number stations remain a matter of scholarly inference rather than confirmed public record, signals intelligence researchers, most notably through the Enigma Control (ENIGMA 2000) catalogue and the publications of the Shortwave Listening community, have attributed a significant fraction of documented number stations to Eastern Bloc intelligence services, including the Bulgarian Darzhavna Sigurnost (DS, State Security) and its Soviet-coordinated counterparts. The physical characteristics of such transmissions—operating frequency, modulation mode, transmission schedule, and apparent geographic origin—are consistent with sites operating in the Sofia region of Bulgaria.

1.2 Scope and objectives

This study addresses the following technical questions:

1. Were horizontally polarised quadrant antennas, in either their Wells cage or single-wire cut-delta configurations, suitable for the propagation of number station transmissions from the Sofia region to target areas in Central Europe, the Mediterranean, and the Near East?
2. What transmitter powers would have been required to achieve reliable reception at those destinations on ordinary shortwave receivers employing single-sideband (SSB) or amplitude-modulated (AM) detection?
3. Which of the three identified candidate transmitter sites—Pobit Kamak (Vakarel), Gorna Malina, and Momina Skala—offered the most favourable operational characteristics for this purpose?

2 The quadrant antenna: technical characteristics

2.1 Wells cage quadrant

The quadrant antenna in its canonical form was described by Wells in 1944 [1] as a horizontally polarised, quasi-omnidirectional radiator for the shortwave bands, employing

two multi-wire cage arms of half-wavelength ($\lambda/2$) each, arranged at 90° in the horizontal plane. The cage construction—employing multiple wires in a cross-shaped or star spreader arrangement—reduces the drive point impedance from the nominally high value of a single-wire $\lambda/2$ resonant element (typically $\approx 5{,}000\,\Omega$ at resonance) to a practically manageable value around $600\,\Omega$, whilst simultaneously broadening the operational bandwidth to approximately an octave. Wells noted the theoretical possibility of single-wire construction but did not pursue it owing to the narrow bandwidth and high drive point impedance [2].

The principal electrical parameters of the Wells cage quadrant at 7.15 MHz, as modelled by Beaumont using EZNEC Pro/2 (a commercial implementation of the Numeric Electromagnetic Code, NEC) [2], are reproduced in Table 1.

Table 1: Principal electrical parameters of the Wells cage quadrant at 7.15 MHz, after Beaumont (2015).

Parameter	**Value**
Operating frequency (design centre)	7.15 MHz
Maximum gain	6.0 dBi
Elevation angle at maximum gain	60°
Drive point impedance	$(608 + j4)\,\Omega$
Azimuth pattern	Quasi-omnidirectional
VSWR bandwidth (≤ 1.25)	7.0 MHz to 7.3 MHz
Polarisation	Horizontal
Recommended mounting height	$\lambda/4$ above ground

The commercial broadcast-grade HQ quadrant, as specified by Ampegon and Transradio SenderSysteme Berlin [3], extends this concept to a multi-dipole cage design supporting operation across two adjacent shortwave broadcasting bands (spanning 5.9 MHz to 26.1 MHz), with a published gain of 7 dBi, a balanced input impedance of $300\,\Omega$, and a maximum rated carrier power of 500 kW.

2.2 Single-wire cut-delta quadrant

Beaumont [2] describes a lightweight amateur variant, designated the *single-wire cut-delta quadrant*, in which the cage arms are replaced by single conductors and the feed arrangement uses a delta-matched section (also known as a cut-delta) to achieve a practical drive point impedance. Key computed parameters at 7.15 MHz for this antenna suspended at $5\lambda/12$ above average ground (conductivity $10\,\mathrm{mS\,m^{-1}}$, dielectric constant 13) are:

- Maximum gain: 5.4 dBi;
- Azimuth variation at 35° elevation: ±0.9 dB;

- Drive point impedance: $(606 - j3)\,\Omega$ at resonance;
- VSWR bandwidth (≤ 2): 6.9 MHz to 7.4 MHz.

Beaumont further notes that suspension at $5\lambda/12$ height was chosen specifically to illustrate coverage to distances of approximately 1,500 km, corresponding to a single ionospheric hop, at approximately constant field strength independent of distance. For a 7 MHz installation, this equates to a physical height of approximately 17.5 m, attainable with modest lattice masts or fortuitously positioned tall structures.

The antenna requires three suspension points in a right-angled triangular plan configuration, a balun transformer (which may be pole-mounted near ground level), and no elaborate ground screen. This simplicity is operationally significant: the antenna can be erected within a compact site perimeter and, in its single-wire form, presents far lower visual, wind-loading, and electromagnetic signature than a large directional curtain array.

2.3 Stacked quadrant configurations

For operation at the upper end of the shortwave spectrum (21 MHz and above), Beaumont [2] describes stacked variants in which two quadrant tiers, separated vertically by $\lambda/2$, are driven in phase. The stacked Wells cage quadrant at 21.225 MHz achieves 9.6 dBi maximum gain at a 17° takeoff angle, substantially suppressing high-angle NVIS radiation in favour of lower-angle skywave suitable for ranges in excess of 2,000 km. Stacked single-wire quadrants at the same frequency achieve 8.4 dBi. These configurations would be relevant if the operational requirement extended to more distant targets such as Israel or Cyprus, as discussed in Section 4.

3 Candidate transmitter sites

Four sites in the Sofia region have been identified as associated with Cold War Bulgarian military, state security, or civil broadcasting radio transmission facilities. Their coordinates, extracted from satellite imagery and published technical records, are given in Table 2. All four lie within approximately 60 km of Sofia city centre.

Satellite imagery of the three primary candidate sites (Pobit Kamak, Gorna Malina, and Momina Skala) confirms the presence of mast structures exceeding 10 m in height. This is directly significant to the antenna engineering analysis that follows: for operation at 7 MHz, the recommended mounting height of the quadrant antenna is approximately $\lambda/4 \approx 10.7$ m, with $\lambda/2 \approx 21.4$ m being preferred for the best low-angle radiation pattern (Section 2). The observed mast heights at all three sites are therefore consistent with, and physically sufficient for, the suspension of a quadrant antenna tuned to the 7 MHz amateur and broadcasting bands. A fourth site, Kostinbrod, is discussed separately in Section 3.4 as a high-power facility whose primary Cold War function was likely jamming rather than covert one-way broadcasting.

Table 2: Radio transmission sites in the Sofia region and wider Bulgaria considered in this study.

Site designation	Latitude (N)	Longitude (E)	Elev.	Role assessed
Pobit Kamak (Vakarel)	42°34′5.7″	23°38′25.8″	∼680 m	Number station candidate
Gorna Malina	42°41′51.2″	23°40′53.4″	∼560 m	Number station candidate
Momina Skala (Vitosha)	42°37′32.1″	23°14′51.9″	∼1,250 m	Number station candidate
Kostinbrod	42°48′33.6″	23°11′3.7″	∼540 m	Civil Bcast / Jamming
Padarsko (Plovdiv)	42°13′48.0″	24°31′12.0″	∼160 m	Civil Bcast / Jamming
Stolnik	42°25′12.0″	23°21′0.0″	∼550 m	Civil Bcast / Jamming

3.1 Pobit Kamak, near Vakarel (42.585°N, 23.641°E)

This site lies on elevated terrain approximately 35 km south-east of Sofia. Satellite imagery indicates cleared land with infrastructure consistent with a former radio installation. The elevated position offers a clear horizon to the north-west, the primary bearing towards Central Europe.

3.2 Gorna Malina (42.698°N, 23.682°E)

Situated on the Sofiysko Pole (Sofia Plain) approximately 30 km north-east of Sofia, this site benefits from flat surroundings with good ground conductivity typical of cultivated plain. Its relatively low elevation provides no topographic shielding, and the flat terrain favours ground-wave coupling at the antenna base, improving the effective radiation of near-vertical incidence skywave (NVIS) at the lower shortwave bands.

3.3 Momina Skala, Vitosha Mountain (42.626°N, 23.248°E)

At approximately 1,250 m above sea level on the southern slopes of Vitosha, this site offers the greatest elevation of the three. The Vitosha massif forms a prominent topographic feature to the south of Sofia, visible from a wide area. An elevated antenna site at this location benefits from reduced near-field ground losses and an unobstructed radiation path to the north-west—towards Austria, Germany, Switzerland, and Italy—and to the

east-south-east towards Turkey and the Levant. The combination of natural elevation and westerly horizon clearance is particularly advantageous for NVIS propagation at 7 MHz to 9 MHz.

3.4 Kostinbrod, Padarsko, and Stolnik: the Bulgarian high-power network

A note on dual-use infrastructure

Before addressing Kostinbrod specifically, it is necessary to establish the correct analytical framework for Bulgarian shortwave infrastructure as a whole. Throughout the Soviet Bloc, high-power shortwave transmitter sites routinely served *dual purposes*: civil international broadcasting and electronic countermeasures (jamming), with the operational role at any given moment depending on the time of day, ionospheric conditions, frequency assignments, and political directives. This was not exceptional practice but standard Warsaw Pact doctrine. The same transmitter and, in many cases, the same antenna could be switched between a Bulgarian National Radio (BNR) programme relay and a jamming signal targeted at Western broadcasters, often within the same broadcast day.

This dual function is directly confirmed by primary archival and field research. Georgiev's doctoral dissertation [13], based on field research at the abandoned Padarsko transmission station in May 2022 and on declassified documents at the Bulgarian Central State Archive (TsDA), establishes that the Padarsko site was explicitly and simultaneously used for both jamming and international radio transmission of Bulgarian programmes abroad. Georgiev's interlocutor, former station technician Hristo Hristev, confirmed that a separate control room directed a local jamming transmitter called "Thunder" while the main facilities operated BNR international services from the same perimeter. Declassified Bulgarian instructions from 1975 for the "organisation and exploitation of the means for radio defense," preserved in TsDA fond 308, explicitly describe the Bulgarian radio defence system as a sub-system of the joint Bulgarian–Soviet radio defence network, with Bulgaria's facilities covering part of Soviet territory whilst Soviet transmitters in the USSR covered Bulgaria's assigned jamming zones [13].

Furthermore, Georgiev documents that in the 1970s the eight most powerful jamming transmitters of 80 kW installed in Bulgaria were ordered and funded by the Soviet Union specifically to cover Soviet territory. A 1974 Ministry of Information report proposed a further 30 transmitters of 100 kW to be installed in three Soviet radio centres at distances of 1000, 2000, and 4000 km from Bulgaria. Engineers at the time explicitly acknowledged that transmission power alone was insufficient and that natural propagation factors—including the day/night cycle and seasonal variations in shortwave propagation—caused effectiveness to "drop dramatically" during certain periods [13]. Published Radio Bulgaria transmission schedules [14] confirm that Kostinbrod carried regular BNR shortwave services in Bulgarian, Russian, German, and other languages alongside its jamming function, while the country-data record for Bulgaria [15] explicitly lists Kostinbrod, Stolnik,

and Plovdiv (Padarsko) as the principal foreign-language shortwave transmission sites.

Kostinbrod (42.809°N, 23.184°E)

Approximately 20 km north-west of Sofia, Kostinbrod is the largest and best-documented of the Sofia-area high-power installations. Published technical records [8] confirm Soviet-supplied transmitters installed between 1979 and 1982:

- 4× 50 kW Soviet PKM-50 transmitters;
- 2× 100 kW Soviet KV-100 transmitters;
- 1× 250 kW Czechoslovak PKV-250 transmitter;
- 1× 15 kW Soviet Molnia 2M transmitter.

The site carried Radio Bulgaria programmes in Russian, German, French, and Bulgarian, with transmissions on 7400 kHz beamed at 30° azimuth (towards the Soviet Union) at 100 kW [14]. The same infrastructure, at the same bearing and on the same or adjacent frequencies, served as a jamming platform when directed by the coordinated Warsaw Pact electronic countermeasures schedule.

Padarsko (near Plovdiv, 42.23°N, 24.52°E) and Stolnik (42.42°N, 23.35°E)

The Padarsko site, on the Thracian Plain near Plovdiv, is the best-documented example of Bulgarian dual-use shortwave infrastructure. It housed 250 kW and 500 kW Soviet PKV-series transmitters [8], with towers reaching 165 m in height [13]. Georgiev's first-hand account of the abandoned facility confirms that the jamming and broadcasting functions occupied physically separate but immediately adjacent control rooms within the same perimeter [13], consistent with the operational requirement for independent scheduling of the two activities whilst sharing common antenna and transmission infrastructure. After 1989 the site was repurposed entirely for Radio Bulgaria programme relays until the cessation of all Bulgarian shortwave services in 2012, when it was systematically demolished [13, 16]. The Stolnik site, 30 km east of Sofia, carried 100 kW and 15 kW transmitters and similarly served both civil broadcasting and countermeasures functions [8, 15].

The geometry of jamming: Radio Liberty at Platja de Pals

The directional logic of shortwave jamming is essential to understanding why Bulgarian sites were valuable to the Warsaw Pact electronic warfare programme. From 1959 to 2001, Radio Liberty's principal shortwave transmitter was located at *Platja de Pals* on Spain's Costa Brava [17, 18], at coordinates 41°59′0″N, 3°12′0″E—approximately 2,900 km from

Moscow. The site was selected by Radio Liberty's chief engineer, Colonel S.Y. McGiffert, specifically for its oceanic foreground, which provided a superior reflecting medium for shortwave signals and allowed single-hop ionospheric propagation to fall entirely within Soviet territory [19]. At its peak, Platja de Pals operated six transmitters of 250 kW each, fed into directional curtain arrays of thirteen towers up to 169 m tall, with a combined effective radiated power that Soviet jamming assets found uniquely difficult to suppress [20].

Table 3: Great-circle bearings from Platja de Pals (Radio Liberty) and from Bulgarian jamming sites to principal Soviet target cities, illustrating the directional geometry of the jamming contest.

Site	**Moscow (°T)**	**Leningrad (°T)**	**Kyiv (°T)**	**Distance to Moscow (km)**
Platja de Pals (Spain)	46.3	33.5	56.3	2902
Kostinbrod (Bulgaria)	30.7	11.8	30.8	1772
Padarsko (Bulgaria)	27.6	9.4	24.6	1775
Stolnik (Bulgaria)	29.8	11.3	29.1	1803

Table 3 reveals the key geometric relationship. Radio Liberty's signal from Pals arrived at Moscow from a bearing of approximately 253° (west-southwest). The Bulgarian jamming transmitters, radiating north-northeastward at 28°–31°, delivered their signals to Moscow from the south-southwest (208°–211°)— a difference of approximately 42° from the Pals arrival bearing. This angular separation matters for *directional* jamming strategies (where the receiving antenna is steered towards the jammed signal) but is largely irrelevant for the dominant Soviet jamming approach: *zone jamming*, in which powerful transmitters saturate the medium-wave and shortwave spectrum within the Soviet Union itself, regardless of the direction from which the Western signals arrive. Under this doctrine, a Bulgarian transmitter beaming high-power interference at the frequencies used by Radio Liberty contributed to the total noise level experienced by Soviet listeners, regardless of its angular relationship to the Pals signal. The closer proximity of Bulgarian sites to Soviet territory (Kostinbrod to Moscow: 1,772 km, versus Pals to Moscow: 2,902 km) also conferred a path-loss advantage of approximately 4 dB, making Bulgarian transmissions proportionally more effective per kilowatt for zone jamming than equivalent-power stations in Western Siberia.

The Bulgarian sites thus served a recognised role in the coordinated Warsaw Pact jamming apparatus—a "barter" arrangement within the socialist broadcasting infrastructure, whereby Bulgaria contributed jamming capacity directed against Radio Liberty and Radio Free Europe in exchange for Soviet technical assistance (the PKM-50, KV-100, and

PKV-250 transmitters were all Soviet or Soviet-bloc supplied) and scheduling coordination through the OIRT (Organisation Internationale de Radiodiffusion et Télévision), the Eastern Bloc counterpart to the EBU.

The central caveat: absence of official disclosure

Before proceeding to any assessment of the high-power sites in relation to number stations, it is essential to acknowledge a fundamental limitation that applies to *all* sites considered in this study: the Bulgarian Government has never published any official information confirming or denying the operation of number stations from Bulgarian territory. This stands in direct contrast to the Czech Republic, whose Office for Foreign Relations and Information (ÚZSI) has acknowledged the use of numbers stations, and to Poland, where the Institute of National Remembrance (IPN) has released documentary evidence of number station operations. No equivalent Bulgarian disclosure exists. All conclusions in this study are therefore probabilistic and inferential, not documentary.

Signal strength evidence and what it does, and does not, tell us

The monitoring records for S02 and E01—the two stations most consistently attributed to Bulgaria—describe signals that were receivable but not particularly strong at typical monitoring locations in Western Europe. No ENIGMA newsletter or systematic monitoring log records either station as a high-power transmission. This is consistent with the 5 W to 25 W operational power range derived in Section 4.4, and is *inconsistent* with the hundreds of kilowatts available at Kostinbrod or Padarsko. Two interpretations are, however, possible:

1. The transmissions were genuinely low-power, originating from one of the smaller candidate sites (Pobit Kamak, Gorna Malina, Momina Skala) using modest, purpose-built transmitters. This is the most straightforward interpretation and is operationally consistent with number station doctrine.

2. The transmissions may have originated from a high-power site such as Kostinbrod, but the monitoring records were made at locations far from the intended coverage zone. A signal from Kostinbrod at 250 kW beamed north-north-east towards the Soviet Union would appear weak at a monitoring receiver located to the north-west (in the United Kingdom, the Netherlands, or Germany), which lies *off the back of the beam*. In such geometry, the received signal level could be consistent with the observed moderate-to-weak reports even from a high-power transmitter.

Crucially, no monitoring record of *high-power* Bulgarian number station transmissions exists either. The absence of strong-signal reports neither confirms nor rules out a high-power origin; it is equally consistent with both a genuinely low-power source and a high-

power directional source monitored from outside its coverage arc. The available signal intelligence record is therefore ambiguous on this point and cannot be used to definitively exclude any site.

Near-field emissions and local witness accounts

A further consideration is the phenomenon of near-field and parasitic emissions from high-power transmitter sites. Residents living near Kostinbrod, Padarsko, and Stolnik during the Cold War era have reported receiving strong, unusual shortwave signals on domestic receivers in the immediate vicinity of these sites—sometimes on frequencies not listed in any official broadcasting schedule. Such reports, whilst anecdotal, are physically explicable by several mechanisms well known to transmitter engineers:

- **Direct-path ground-wave and near-field radiation.** At distances of a few kilometres from the transmitter, the antenna's near field and ground-wave component may deliver substantial signal strength to receivers within line of sight of the antenna structure, regardless of the main beam elevation angle. NVIS and high-angle antennas—including the quadrant—radiate the majority of their energy skyward, but residual near-horizontal components at ground level remain detectable in the vicinity of the installation.
- **Harmonic and spurious emissions.** High-power transmitters, particularly older Soviet-era valve designs, generate harmonic and intermodulation products that may appear at integer multiples or combination frequencies of the fundamental. A 100 kW transmitter on 7 MHz may produce a second harmonic at 14 MHz at 100 W to 500 W effective radiated power—entirely sufficient for local reception without appearing in any official schedule.
- **Feeder radiation.** Open-wire feeders, imperfectly balanced coaxial runs, and unshielded balun transformers can re-radiate a fraction of the transmitted power as an unintentional ground-level omnidirectional source. At high power levels, even a -40 dB leakage fraction yields milliwatts to watts of stray radiation—more than sufficient for a local receiver.

These mechanisms mean that unusual transmissions heard at close range near any of the documented sites cannot reliably be attributed to intentional clandestine broadcasts; they may equally represent incidental artefacts of normal transmitter operation. Equally, however, they demonstrate that a number station transmission *could* have been operated from such a site without being distinguishable as a distinct signal by local observers.

Revised assessment: all sites remain possible

Reconsidering the full picture in the light of these constraints, this study revises its site assessment as follows. All six sites in Table 2—including Kostinbrod, Padarsko, and Stolnik—must be regarded as *technically capable* of supporting number station operations, subject to the following qualifications:

The three primary candidate sites (Pobit Kamak, Gorna Malina, Momina Skala) remain the *most operationally plausible* for number station use, on grounds of power economy, infrastructure simplicity, and low observability. They require no adaptation of civil or jamming infrastructure, no operational cover story, and no high-power equipment.

The three high-power sites (Kostinbrod, Padarsko, Stolnik), despite their scale and dual-use function, cannot be categorically excluded. The dual-use character of all Warsaw Pact broadcast infrastructure means that any of these sites could, at given hours or on specific frequencies, have operated a low-observable narrowband transmission alongside their primary schedule, or could have used their infrastructure to support a separate, low-power transmitter co-located within the same perimeter. The absence of Bulgarian official disclosure makes it impossible to confirm or deny this. The weak signal records for S02 and E01 are more naturally consistent with a modest dedicated transmitter, but the monitoring geometry cannot be established with certainty.

The conclusion of this study is that the present study establishes *technical feasibility* across all sites and *operational plausibility* at the three primary candidate sites, but falls short of attribution—as must any study conducted without access to the relevant Bulgarian State Security archives.

4 Propagation analysis and coverage assessment

4.1 Frequency selection and propagation mode

For the range of target distances under consideration (476 km to 1,603 km), the principal propagation mechanism is single-hop ionospheric skywave, predominantly via the F2 layer at night and the F1 or combined F-layer during daylight hours. For distances up to approximately 1,000 km, near-vertical incidence skywave (NVIS) represents the dominant mode; for greater distances, oblique skywave at elevation angles of 15° to 35° becomes important.

The following frequency–distance guidance applies under typical mid-latitude ionospheric conditions:

All of the listed frequencies lie within the operational range of the HQ commercial quadrant (5.9 MHz to 26.1 MHz) and within the usable range of the single-wire cut-delta quadrant with appropriate scaling of arm dimensions.

Table 4: Recommended operating frequencies for target distances from the Sofia region.

Distance range (km)	Night (MHz)	Day (MHz)
400 to 800	7–9	9–11
800 to 1,300	7–11	11–15
1,300 to 1,600	9–13	13–17

4.2 Great-circle distances and bearings from each site

Tables 5, 6, and 7 present the geodetic great-circle distances and true bearings from each transmitter site to the principal cities of each target country. Distances flagged with † exceed the published maximum coverage radius of the quadrant antenna at its rated maximum power of 500 kW; these are discussed separately in Section 4.5.

Table 5: Great-circle distances and bearings: Pobit Kamak (Vakarel).

City	Country	Distance (km)	Bearing (°T)
Vienna	Austria	844	320.3
Salzburg	Austria	1011	308.7
Munich	Germany	1124	307.4
Berlin	Germany	1343†	328.9
Frankfurt	Germany	1416†	311.4
Milan	Italy	1197	290.4
Rome	Italy	920	269.0
Zurich	Switzerland	1299	299.4
Bern	Switzerland	1364†	296.4
Ankara	Turkey	825	108.0
Istanbul	Turkey	476	109.8
Athens	Greece	512	179.1
Nicosia	Cyprus	1177	131.1
Jerusalem	Israel	1577†	135.9
Tel Aviv	Israel	1525†	136.3

Table 6: Great-circle distances and bearings: Gorna Malina.

City	Country	Distance (km)	Bearing (°T)
Vienna	Austria	836	319.6
Salzburg	Austria	1006	308.0
Munich	Germany	1119	306.8
Berlin	Germany	1334†	328.5
Frankfurt	Germany	1411†	310.9

(continued)

City	Country	Distance (km)	Bearing (°T)
Bern	Switzerland	1362†	295.9
Ankara	Turkey	825	108.9
Istanbul	Turkey	477	111.4
Athens	Greece	524	179.6
Nicosia	Cyprus	1182	131.7
Jerusalem	Israel	1584†	136.3
Tel Aviv	Israel	1531†	136.8

Table 7: Great-circle distances and bearings: Momina Skala (Vitosha).

City	Country	Distance (km)	Bearing (°T)
Vienna	Austria	820	321.6
Salzburg	Austria	983	309.4
Munich	Germany	1096	308.0
Berlin	Germany	1322†	329.7
Frankfurt	Germany	1389†	311.8
Milan	Italy	1165	290.5
Rome	Italy	888	268.4
Zurich	Switzerland	1269	299.6
Bern	Switzerland	1333†	296.5
Ankara	Turkey	857	107.3
Istanbul	Turkey	508	108.8
Athens	Greece	518	175.3
Nicosia	Cyprus	1204	130.0
Jerusalem	Israel	1603†	134.9
Tel Aviv	Israel	1550†	135.3

† Exceeds the published 1,300 km maximum coverage radius for the HQ quadrant at 500 kW; see Section 4.5.

4.3 Geometric analysis: bearing arcs

Inspection of the bearing data reveals a particularly convenient geometric property of all three sites relative to the target distribution. The north-western targets (Austria, Germany, Switzerland, northern Italy) lie within a bearing arc of approximately 290° to

332°, whilst the south-eastern targets (Turkey, Greece, Cyprus, Israel) lie within a bearing arc of 107° to 180°. These two arcs are effectively diametrically opposed.

An omnidirectional antenna such as the quadrant therefore simultaneously illuminates *both* arcs from a single fixed installation, with no requirement for phased arrays, beam steering, or multiple directional curtain antennas. This is of substantial operational significance: a clandestine facility equipped with a quadrant antenna could address agents in Vienna, Rome, Istanbul, and Athens simultaneously from a single transmission, on a single frequency and schedule, without any change in antenna orientation or transmitter configuration.

4.4 RF link budget

The received signal power P_r at an agent's receiver may be expressed via the Friis transmission equation adapted for ionospheric skywave propagation:

$$P_r = P_t + G_t - L_p - L_a - L_f + G_r \tag{1}$$

where all quantities are in dBm or dB as appropriate, and:

$$\begin{aligned} P_t &= \text{transmitter output power (dBm)}, \\ G_t &= \text{transmitting antenna gain relative to isotropic (dBi)}, \\ L_p &= \text{ionospheric path loss (dB)}, \\ L_a &= \text{ionospheric absorption loss (dB)}, \\ L_f &= \text{fading margin (dB)}, \\ G_r &= \text{receiving antenna gain (dBi)}. \end{aligned}$$

The correct performance criterion: intelligibility, not broadcast quality

A fundamental distinction must be drawn between the performance standard applicable to international broadcasting and that applicable to number station reception. A broadcast service must be reliably intelligible to a general population of listeners using consumer-grade receivers under varying conditions, demanding a signal-to-noise ratio (SNR) of 16 dB or more above the noise floor and a generous fading margin.

A number station, by contrast, operates to an entirely different standard. The receiving agent is a *trained individual*, listening at a *known time* on a *known frequency*, for a *known format*: slow, clearly enunciated, repeated five-figure groups. Speech intelligibility research and operational practice consistently show that digit recognition in a known format is achievable at SNR values as low as +3 dB to +6 dB above the noise floor—a threshold roughly 10 dB below that required for comfortable general broadcasting. High

transmitter power is not an operational requirement; it is a liability. A powerful signal radiating omnidirectionally is readily detected, direction-found, and attributed. The correct engineering objective for a number station transmitter is the *minimum power sufficient to achieve digit intelligibility at the agent's location*, with a modest fading margin only.

The governing noise source: external HF atmospheric and man-made noise

At the documented Bulgarian station frequencies (4.74 MHz to 6.675 MHz), the noise environment at a receiving location in Central or Southern Europe is not limited by the thermal noise floor of the receiver but by *external* atmospheric and man-made HF noise, as characterised by ITU-R Recommendation P.372 [5]. For a suburban or rural European location at these frequencies during nighttime hours, the external noise figure F_a is approximately 55 dB above the thermal reference (kTB). This overwhelms any reasonable receiver noise figure and sets the effective noise floor far above the thermal limit:

$$N_{\text{eff}} = kTB \cdot 10^{F_a/10} \tag{2}$$

For a narrowband AM receiver with a 3 kHz audio bandwidth (appropriate to number station voice), the effective noise floor is therefore approximately $-139 + 55 = -84$ dBm. This is the figure that governs minimum received signal requirements—not the receiver's own thermal noise floor.

Minimum power calculation

Table 8 presents the computed minimum transmitter power required to achieve digit intelligibility (SNR $\geq +6$ dB above the external noise floor, with a 10 dB fading margin) at each primary target, using the cut-delta quadrant (5.4 dBi) at the transmitter and a short random wire (1.5 dBi) at the receiving end—the most operationally conservative receiving antenna assumption, consistent with an agent using a few metres of wire in an apartment.

The results are striking. For the closest targets (Istanbul, Athens), a transmitter power of tens of milliwatts is physically sufficient for intelligibility; a standard 10 W transmitter provides more than 23 dB of margin above the minimum. For the primary Central European target, Vienna at 820 km, the minimum power is approximately 500 mW, and a 10 W transmitter yields 13 dB of margin—amply robust against typical nighttime fading whilst remaining entirely inconspicuous. Even at Munich (1,097 km) and Nicosia (1,180 km), transmitter powers of 5 W to 10 W exceed the intelligibility threshold by 4 dB to 8 dB.

Table 9 further illustrates the relationship between transmitter power and reception quality at the Vienna benchmark distance.

Table 8: Minimum transmitter power for number station digit intelligibility. External noise: ITU-R P.372 $F_a = 55\,\text{dB}$ (suburban Europe, nighttime). Narrowband AM, 3 kHz BW; SNR threshold +6 dB; fading margin 10 dB; $G_t = +5.4\,\text{dBi}$ (cut-delta quadrant); $G_r = +1.5\,\text{dBi}$ (short wire).

Target	**Dist. (km)**	**Path loss (dB)**	$P_{\min}$ **(W)**	**10 W margin (dB)**
Istanbul (4.74 MHz)	477	90	0.03	+25
Athens (6.675 MHz)	512	92	0.05	+23
Vienna (5.5 MHz)	820	101	0.39	+14
Vienna (6.675 MHz)	820	102	0.49	+13
Munich (6.675 MHz)	1097	108	1.95	+7
Nicosia (6.675 MHz)	1180	110	3.09	+5

Table 9: Reception quality as a function of transmitter power: Vienna (820 km), 6.675 MHz, nighttime. Minimum intelligibility power: $\approx 0.5\,\text{W}$.

Tx power	**Margin above** $P_{\min}$	**Assessment**
1 W	+3 dB	Marginal; copies on good nights
5 W	+10 dB	Reliable intelligibility most nights
10 W	+13 dB	Good; robust against moderate fading
25 W	+17 dB	Excellent; effective on virtually all nights
50 W	+20 dB	Unnecessary excess; no operational benefit
100 W	+23 dB	Broadcast-grade; operationally counterproductive

The operationally optimal transmitter power for the Sofia–Central Europe path is therefore in the range of 5 W to 25 W. This power level is achievable with a compact, mains-powered or even battery-operated shortwave transmitter of the type readily available to any intelligence service during the Cold War period, requires no forced-air cooling, leaves no electromagnetic or thermal signature visible at site perimeter distances, and is entirely consistent with the low-observable character of a covert number station installation.

4.5 Targets beyond 1300 km: extended range

The published maximum coverage radius of the commercial HQ broadcast quadrant at 500 kW is 1,300 km [3]. This specification is, once again, a broadcast-grade figure applicable to mass audiences with unspecified receiver quality. For a dedicated agent receiver with a purpose-tuned antenna, and given the intelligibility-threshold criterion established above, the effective coverage of a 25 W narrowband AM transmission at 6.675 MHz extends well beyond 1,300 km on favourable ionospheric nights. Berlin (1,322 km to 1,343 km) and Frankfurt (1,389 km to 1,416 km) fall within this extended range, as does Nicosia (1,180 km), which is already covered within the primary power budget of Table 8. For Israel (1,525 km to 1,603 km), a higher frequency (9 MHz to 11 MHz) or slightly higher power (50 W to 100 W) would be required to achieve a robust intelligibility margin under average conditions, but neither represents any departure from a low-observable transmitter installation.

The critical operational conclusion is that **no site-revealing infrastructure is required at any distance considered in this study**. Numbers station operations are inherently narrowband and intelligibility-limited, not bandwidth- or quality-limited. The entire operational requirement—from Istanbul to Munich to Nicosia—is met by a transmitter that could fit in a small suitcase and run from a standard 220 V domestic supply, with a quadrant antenna indistinguishable from a routine military communications wire installation.

5 Comparative site assessment

5.1 Scoring criteria

The three candidate sites are assessed against the following criteria, each on a notional scale relevant to Cold War clandestine operations:

1. **Proximity to primary target bearing arc** (NW, towards Central Europe);
2. **Ground conductivity and topographic clearance** for NVIS propagation;
3. **Low observability** (site concealment, plausible civilian cover);
4. **Logistics and infrastructure access** (road access, power supply);
5. **Distance from Sofia** (proximity to command and control).

5.2 Assessment summary

Gorna Malina presents the most favourable overall profile. Its position on the flat Sofia Plain provides the best ground conductivity for NVIS propagation, offers unobstructed

horizons in all azimuths, and lies within 30 km of Sofia with good road access. The comparatively lower elevation (560 m) is not a disadvantage for NVIS-dominated propagation at 7 MHz to 9 MHz, where antenna height above ground in wavelengths is the governing parameter, not altitude above sea level per se.

Pobit Kamak (Vakarel) offers a modest topographic advantage to the north-west and benefits from elevated terrain. However, the south-easterly shift in position slightly increases bearings to Central European targets and marginally reduces coverage of the western Italian sector.

Momina Skala (Vitosha), despite its imposing elevation of 1,250 m, presents certain operational disadvantages. The Vitosha massif itself may introduce topographic shielding at low elevation angles to the south and east, and the site is more visible and accessible than a plain-based installation. However, the high elevation does benefit radiation at low takeoff angles in the north-westerly direction and would be particularly advantageous if a stacked cage quadrant—with its characteristic low-angle gain enhancement of 9.6 dBi at 17° elevation [2]—were employed for coverage of more distant targets.

6 Operational considerations and covertness

6.1 Antenna observability

The single-wire cut-delta quadrant, with arm lengths of approximately 14 m at 7.15 MHz, can be erected between three timber poles or between conveniently positioned trees and presents minimal visual signature. It requires no large lattice mast. Beaumont notes that the first proof-of-concept installation used three trees in a domestic garden. An intelligence service operating under the cover of a civilian shortwave relay station, an agricultural radio link, or a military communications post would have found this antenna unexceptional in appearance.

The Wells cage quadrant, whilst larger and more visually prominent, is identical in external appearance to a legitimate international broadcasting antenna and would attract no attention at a site already designated as a radio transmission facility.

6.2 Frequency agility and schedule discipline

Number station operations are characterised by strict frequency and schedule discipline: a fixed frequency and transmission time known only to the intended recipient and the originating service. The quadrant's operational bandwidth of approximately one octave (for the cage design) or a single amateur band segment (for the single-wire cut-delta) supports selective operation on a pre-assigned frequency without the need for real-time tuning or switching, reducing the number of operators and mechanical components required.

6.3 Direction-finding resistance: the role of the azimuth radiation pattern

A property of the quadrant antenna that has not previously been discussed in the context of clandestine radio operations, but which is of direct operational relevance, is its inherent resistance to direction-finding (DF). This resistance arises directly from the omnidirectional azimuth pattern that is the quadrant's defining characteristic, and it applies regardless of whether the monitoring organisation was the Cold War-era ENIGMA listening network, a national SIGINT service, or a military DF network.

The physical basis of direction-finding

Conventional shortwave DF receivers—whether rotating loop aerials, Adcock arrays, or aperture-synthesis Wullenweber installations (colloquially known as "elephant cage" arrays)—determine the bearing to a transmitter by exploiting the *angular variation* of the received signal amplitude as a function of azimuth. The fundamental parameter governing DF accuracy is the rate of change of antenna gain with azimuth, $\mathrm{d}G/\mathrm{d}\theta$, at the bearing of interest. For a directive antenna with a narrow main lobe, this derivative is large on the lobe flanks, producing a sharp and unambiguous bearing estimate. The Cramér–Rao lower bound on bearing estimation error for a directive transmitting antenna with azimuth beamwidth $\theta_{3\,\mathrm{dB}}$ and received signal-to-noise ratio S (linear) is approximately:

$$\sigma_\theta \approx \frac{\theta_{3\,\mathrm{dB}}}{2\sqrt{2S}} \tag{3}$$

For a curtain array with $\theta_{3\,\mathrm{dB}} = 30^\circ$ operating at $S = 20\,\mathrm{dB}$ ($S_{\mathrm{lin}} = 100$), Equation (3) yields $\sigma_\theta \approx 1.1^\circ$. At this bearing precision, two DF stations separated by 500 km (e.g. Vienna and Munich) produce cross-bearing position uncertainties of approximately 15 km to 20 km at 900 km range—sufficient to resolve an individual transmitter site within the Sofia region.

The quadrant: near-zero azimuth gradient

The quadrant antenna presents an entirely different situation. As documented by Beaumont [2], the cut-delta quadrant at 7.15 MHz suspended at $5\lambda/12$ height exhibits an azimuth gain variation of only $\pm 0.9\,\mathrm{dB}$ at 35° elevation (Fig. 2 of the reference), whilst the commercial HQ broadcast quadrant is specified as omnidirectional [3]. A gain variation of $\pm 0.9\,\mathrm{dB}$ across the entire 360° azimuth corresponds to a gradient $\mathrm{d}G/\mathrm{d}\theta$ that is, for practical purposes, indistinguishable from zero at any bearing. In the limit of a truly omnidirectional pattern, $\mathrm{d}G/\mathrm{d}\theta = 0$ everywhere and Equation (3) becomes singular—the Cramér–Rao bound on bearing error is unbounded, meaning that a DF receiver exploiting only the amplitude variation of the received signal cannot extract a meaningful bearing estimate at all.

In practice, the near-omnidirectional character of the quadrant means that a rotating loop or Adcock DF receiver, which relies on finding a signal maximum or null as the antenna rotates, cannot form a well-defined null or peak in the azimuth response. The result is a broad, shallow azimuth variation from which a bearing can be estimated only with large uncertainty. Table 10 quantifies the cross-bearing position uncertainty for several representative transmitter antenna types, assuming a realistic Cold War-era DF bearing error.

Table 10: Direction-finding bearing error and position uncertainty at 900 km range as a function of transmitting antenna type. Two DF stations separated by 500 km, SNR = 20 dB.

Transmitting antenna	**Azimuth BW**	**Bearing error (σ_θ)**	**Cross-range uncertainty at 900 km**
Curtain array (HRS-4/4)	30°	$\approx 1°$	≈16 km
Rhombic	20°	$\approx 0.7°$	≈11 km
Half-wave dipole (broadside)	78°	$\approx 2.8°$	≈44 km
Quadrant (cut-delta / HQ)	±0.9 dB variation	$\gg 10°$	≫160 km

At a realistic bearing uncertainty of 10° or greater for an omnidirectional source, the cross-bearing position fix at 900 km range has a cross-range uncertainty exceeding 160 km. This is larger than the entire Sofia region under study: the three primary candidate sites (Pobit Kamak, Gorna Malina, and Momina Skala) are all within 60 km of Sofia city centre and cannot be distinguished from one another—or even from Sofia itself—under these conditions.

TDOA methods and their Cold War limitations

Time-difference-of-arrival (TDOA) techniques, which compare the phase or timing of a signal received at multiple geographically separated stations, are in principle independent of the transmitting antenna pattern and could resolve the bearing ambiguity of an omnidirectional source. However, effective TDOA-based geolocation during the Cold War period required simultaneous reception at three or more well-separated stations with synchronised clocks or a common timing reference, together with the computational infrastructure to cross-correlate wideband recordings. Such capabilities existed within national SIGINT agencies (particularly NSA and GCHQ), but the ENIGMA monitoring community and similar civilian shortwave listeners were entirely without them. Furthermore, TDOA accuracy for a narrowband, low-power AM transmission on an interband frequency is further limited by ionospheric multipath: the signal arrives at each receiving station via multi-

ple ionospheric paths with slightly different delays, broadening the cross-correlation peak and degrading timing precision. This effect is most pronounced at the lower frequencies (4.74–6.675 kHz) documented for the Bulgarian number stations, where NVIS propagation produces multiple closely spaced ionospheric reflection paths.

Implication for location attribution

The combined effect of the near-omnidirectional radiation pattern and the interband frequency selection of S02 and E01 is that these transmissions were, from a DF perspective, maximally difficult to locate precisely. Even a well-equipped Cold War SIGINT service using conventional bearing-finding equipment could at best determine that the transmitter was somewhere within a broad arc extending through Bulgaria and the surrounding region, without being able to distinguish between the candidate sites within the Sofia area or, indeed, between Sofia and other potential origins in the wider Balkan region. This is consistent with the ENIGMA community's attribution of these stations to Bulgaria as a country rather than to any specific transmitter site, and it constitutes an additional operational argument in favour of the quadrant antenna for this application beyond its propagation and power economy characteristics.

6.4 Power economy, covertness, and site observability

The link budget analysis of Section 4.4 establishes that the entire operational requirement of a number station serving the Sofia–Central Europe and Sofia–Eastern Mediterranean target arcs is met by a transmitter in the range of 5 W to 25 W. This is the most operationally significant finding of the present study.

A transmitter of this power class is entirely unremarkable. It occupies a volume comparable to a domestic audio amplifier, requires no forced-air cooling, draws less than 100 W from a standard 220 V domestic mains supply, and produces no externally detectable electromagnetic or thermal signature at distances exceeding a few tens of metres. It can be operated from a vehicle, a converted outbuilding, or a room in an otherwise unremarkable residential or administrative building. It produces no detectable radio-frequency interference to neighbouring equipment at distances beyond the immediate premises.

This is in direct contrast to the 500 kW transmitters of the Kostinbrod jamming facility, whose power supply infrastructure, cooling systems, and ground radial networks are visible from satellite imagery and whose broadband radio-frequency emission is detectable by monitoring services at intercontinental distances.

The key operational principle is that high power is not only unnecessary for number station use—it is actively counterproductive. A high-power transmission can be detected by signals intelligence (SIGINT) assets at long range, direction-found by triangulation, and used to localise the originating facility. A 10 W narrowband AM transmission on an interband utility frequency, by contrast, lies within the ambient HF noise environment

of any monitoring receiver operating beyond approximately 500 km from the transmitter, whilst remaining entirely adequate for a trained agent at a known frequency and time.

7 Frequency cross-check: documented number station transmissions versus Beaumont antenna design bands

7.1 Stations attributed to Bulgaria in the ENIGMA records

The ENIGMA Control List and its successor, the ENIGMA 2000 Active Station List [6], record two number stations for which a Bulgarian origin has been proposed or confirmed by the monitoring community:

- **S02** (*Drums and Trumpets*): A Slavic-language station broadcasting in Bulgarian, operated by Bulgarian intelligence. The preamble consisted of the bugle call *Il Silenzio* (also tracked separately as X01), followed by an automated male and female voice reading five-figure groups. Confirmed inactive since 1996 [11]. Documented transmission frequencies: **4740, 5500, 6675 kHz**.
- **E01** (*Ready, Ready!*): An English-language station using an automated female voice, attributed by some researchers to Bulgaria on the basis that it shared transmission frequencies and structural similarities with S02 [12]. Its country of origin is reported as unconfirmed, with Bulgaria, Italy, and the United States each proposed. Inactive since approximately 1999. Documented transmission frequencies: **4740, 5500, 6675 kHz** (shared with S02).

Both stations transmitted in AM mode. Neither Priyom.org nor the ENIGMA newsletters record additional frequencies beyond the three shared values for S02 and E01; it should be noted that number station frequency logs from the Cold War period are inherently incomplete, and additional channels may have been used at times not captured in the public record.

7.2 Physical antenna parameters at the documented frequencies

The three documented frequencies—4740 kHz, 5500 kHz, and 6675 kHz—fall in the 60/75 metre and 49 metre shortwave regions. Table 11 presents the principal physical parameters of a cut-delta quadrant antenna, scaled from Beaumont's reference design at 7.15 MHz [2], for each documented frequency.

All three frequencies require arm lengths between 15 m and 21 m and $\lambda/4$ mast heights between 11 m and 16 m. These are entirely practical dimensions: they closely bracket Beaumont's modelled reference design, and as previously noted in Section 3, satellite imagery confirms mast structures exceeding 10 m at all three candidate sites. The physical infrastructure observed is therefore consistent with, and sufficient for, operation at any of the three documented frequencies.

Table 11: Physical parameters of a cut-delta quadrant scaled to documented Bulgarian number station frequencies, after Beaumont (2015), ref. design at 7.15 MHz: arm outer tip = 14.185 m, $\lambda/4$ height = 10.43 m.

Freq. (kHz)	**Freq. (MHz)**	**λ (m)**	**Arm outer tip (m)**	**$\lambda/4$ height (m)**
4740	4.740	63.3	21.4	15.8
5500	5.500	54.5	18.4	13.6
6675	6.675	44.9	15.2	11.2
Beaumont ref. (7150 kHz)		41.9	14.2	10.4

7.3 Relationship to the commercial HQ quadrant band plan

A comparison of the three documented frequencies against the shortwave broadcasting band allocations listed in the commercial HQ quadrant specification [3] reveals a noteworthy discrepancy: none of the three frequencies falls within a standard WARC-92 shortwave broadcasting band. The nearest standard allocation is the 49 metre band (5.90 MHz to 6.20 MHz); the 6675 kHz frequency lies approximately 475 kHz above its upper edge, and 4740 kHz and 5500 kHz lie entirely below the lowest WARC-92 shortwave broadcasting allocation.

This observation is significant in two respects. First, it confirms that the documented Bulgarian number stations were *not* using standard international broadcasting frequencies, which would have subjected them to ITU coordination and monitoring. By operating in the interstices between allocated bands—in what radio engineers sometimes describe as "interband" or "utility" spectrum—the transmissions avoided the ordinary shortwave broadcast monitoring infrastructure whilst remaining fully audible to any receiver tuned to those channels. This is consistent with established number station tradecraft.

Second, it demonstrates that the commercial HQ broadcast quadrant, designed specifically for the standard WARC-92 shortwave broadcasting bands, was *not* the antenna type employed. Rather, the documented frequencies are consistent with a purpose-tuned quadrant antenna—either a Wells cage quadrant or a Beaumont-style cut-delta—dimensioned specifically for the operational frequencies, scaled upward in arm length and mast height from Beaumont's 7 MHz reference design.

7.4 Propagation regime at the documented frequencies

At 4740 kHz and 5500 kHz ($\lambda \approx 55$–63 m), the dominant propagation mechanism for paths of 400 km to 1,100 km is near-vertical incidence skywave (NVIS), with the majority of radiated energy returning to ground at large angles. This is advantageous for the medium-range targets (Vienna at 820 km, Istanbul at 477 km, Athens at 512 km) and provides inherent resistance to ground-wave and low-angle interference. Ionospheric propagation at

these frequencies is reliable only during nighttime and twilight hours, when the absorbing D-layer has decayed, which is consistent with operational security considerations: number station broadcasts are typically scheduled for evening or night-time hours to minimise the risk of daytime monitoring.

At 6675 kHz, the propagation regime is transitional between NVIS and oblique skywave, extending reliable coverage to approximately 500 km to 1,300 km under nighttime conditions. This frequency therefore provides the widest effective coverage of the three, including Nicosia (1,180 km) and the nearer German and Austrian cities.

Beaumont's cut-delta quadrant, modelled at 7.15 MHz with a suspension height of $5\lambda/12 \approx 17.5$ m, was designed specifically—in Beaumont's own words—"to yield approximately constant field strength, independent of distance, for signals out to about 1,500 km, i.e. a single ionospheric hop" [2]. A design scaled to 6.675 MHz with the same proportional geometry would achieve the same coverage objective. A design scaled to 4.740 MHz would require a suspension height of approximately $5\lambda/12 \approx 26.4$ m and arm tips at 30 m—substantially larger, and more consistent with the structures one would expect at a permanent military transmission facility than at an amateur installation, but still well within the scope of a modest lattice mast.

7.5 Interim conclusion

The documented operating frequencies of the Bulgarian-attributed number stations S02 and E01 are fully consistent with operation on a purpose-scaled quadrant antenna of the cut-delta or Wells cage type. The required physical dimensions are practical, bracket those of Beaumont's reference design, and match the mast heights confirmed by satellite imagery at the candidate sites. The frequencies were deliberately selected outside the standard WARC shortwave broadcasting allocations, precluding use of a standard commercial HQ broadcast quadrant but entirely compatible with a bespoke, frequency-specific quadrant installation. The NVIS-dominant propagation at these frequencies is well matched to the primary target distances (Istanbul, Athens, Vienna, Munich) and to the characteristic nighttime scheduling of Cold War number station operations.

8 Conclusions

9 Conclusions

The following conclusions are drawn from the foregoing analysis. Given that the Bulgarian Government has never published any official information on number station operations—unlike the Czech and Polish governments, which have released relevant documentary evidence—all conclusions are necessarily inferential and probabilistic in character.

1. The near-omnidirectional azimuth pattern of the quadrant antenna confers a signifi-

cant additional operational advantage: resistance to direction-finding. Conventional DF techniques exploiting azimuth signal variation cannot form a meaningful bearing estimate against a transmitter whose azimuth gain varies by only ±0.9 dB across the full 360°. The resulting bearing uncertainty of $\gg 10°$ translates to a cross-range position uncertainty exceeding 160 km at 900 km range (Section 6.3), larger than the entire Sofia region. This is consistent with the ENIGMA community's attribution of S02 and E01 to Bulgaria as a country without being able to identify any specific transmitter site—a level of precision that could not have been improved upon with the equipment available to civilian monitoring organisations during the Cold War.

2. Horizontally polarised quadrant antennas, whether in the Wells cage or single-wire cut-delta configuration, are technically well suited to the propagation of clandestine shortwave number station transmissions from the Sofia region of Bulgaria. The omnidirectional azimuth pattern of the quadrant is its defining operational advantage: a single fixed antenna simultaneously addresses the north-western arc (Austria, Germany, Switzerland, Italy) and the south-eastern arc (Turkey, Greece, Cyprus, Israel) without beam switching or multiple installations.

3. The documented transmission frequencies of the two Bulgarian-attributed number stations—S02 (*Drums and Trumpets*) and E01 (*Ready, Ready!*)—are 4740 kHz, 5500 kHz, and 6675 kHz. All three fall outside the standard WARC-92 shortwave broadcasting allocations, consistent with interband utility operation below the monitoring threshold of the ordinary shortwave broadcast logging community. A purpose-scaled cut-delta or Wells cage quadrant at these frequencies requires arm lengths of 15 m to 21 m and mast heights of 11 m to 16 m—dimensions that bracket Beaumont's reference design and are consistent with mast infrastructure observed at the primary candidate sites.

4. Applying the correct operational criterion—digit intelligibility for a trained agent, not broadcast quality—transmitter powers of 5 W to 25 W are sufficient for the primary target arc to 1,200 km. The observed moderate-to-weak signal strength of S02 and E01 in Western European monitoring logs is consistent with this power range. No high-power Bulgarian number station transmission has been recorded. However, this negative evidence does not conclusively exclude a high-power source: a large directional transmitter beamed north-north-east (towards the Soviet Union) would appear weak at monitoring receivers positioned to the north-west, off the back of the beam. The signal record is ambiguous and cannot resolve the question of transmitter site.

5. All six sites in Table 2 are *technically capable* of supporting number station operations. The three primary candidate sites (Pobit Kamak, Gorna Malina, Momina Skala) are assessed as the most *operationally plausible* on grounds of power economy, infrastructure simplicity, and low observability. The high-power sites (Kostinbrod, Padarsko, Stolnik) cannot be categorically excluded: the dual-use character of all

Warsaw Pact shortwave infrastructure means that a narrowband low-power transmission could in principle have operated from within any of these perimeters alongside the primary schedule, without being distinguishable from routine transmitter artefacts by external observers.

6. Near-field and parasitic emissions from high-power transmitter sites— direct groundwave radiation within the antenna near field, harmonic and intermodulation products from valve-based transmitters, and stray feeder radiation from imperfectly balanced open-wire transmission lines—provide a credible physical explanation for unusual shortwave signals reported by residents in the vicinity of these installations during the Cold War period. Such near-field reception does not confirm intentional clandestine broadcasting, but it illustrates that any of these sites could have hosted a covert narrowband transmitter without it being identifiable as such by local witnesses.

7. Gorna Malina remains the most favourable of the primary candidate sites on propagation, logistical, and concealment grounds. Momina Skala is the most favourable for coverage of more distant targets using a stacked quadrant configuration.

8. The fundamental conclusion of this study is one of *technical feasibility across all sites, operational plausibility at the three primary candidate sites, and irresolvable ambiguity on attribution.* The latter can only be resolved by access to Bulgarian State Security (DS) archives, which remain largely classified or "missing". In the absence of such access, this study establishes the RF engineering case that the identified Sofia-region sites possessed the physical infrastructure, the propagation geometry, and the power capabilities consistent with the documented characteristics of Bulgarian-attributed Cold War number station transmissions.

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